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Temperature-Controlled Bending of a Gun Tube

Mark Bundy

ARL-MR-315 June 1996

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REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	June 1996	Final, Dec 1994 - 1995

4. TITLE AND SUBTITLE
Temperature-Controlled Bending of a Gun Tube

5. FUNDING NUMBERS
PR: 1L162618AH80

6. AUTHOR(S)
Mark Bundy

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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ATTN: AMSRL-WT-PB
Aberdeen Proving Ground, MD 21005-5066

8. PERFORMING ORGANIZATION REPORT NUMBER
ARL-MR-315

9. SPONSORING/MONITORING AGENCY NAMES(S) AND ADDRESS(ES)

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

For some ammunition types, the projectile impact location appears to be gun tube dependent, even though the aim point, barrel mount, and ammunition lot may be the same. It is thought that such barrel dependency is due to manufactured differences in the straightness of each tube. To test this hypothesis, we have devised a means to reversibly control the centerline curvature of a gun tube. This preliminary report describes how a series of heating pads, adhered to the external surface of the barrel, can be used to change the bore centerline curvature. Several centerline alterations are demonstrated on a 120-mm M256 tank cannon. The theoretical prediction for each of several heat-pad-induced centerline changes compares favorably with borescope measurements of the muzzle angle change and dial-indicator measurements of the outer-wall barrel displacement. Future gun firings of this temperature-controlled barrel will be used to examine the correlation between shot impact location and centerline curvature.

14. SUBJECT TERMS
accuracy, modeling, gun barrel, controlled centerline bend, distortion

15. NUMBER OF PAGES
29

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

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1. INTRODUCTION

The difference between where a gun is aimed (correcting for gravity drop, wind, and drag) and where the projectile actually strikes the target is referred to as projectile jump. Factors that contribute to projectile jump include, but are not limited to (Bornstein et al. 1988): (1) the muzzle angle and (2) its transverse velocity at shot exit, as well as (3) asymmetric sabot discard (for kinetic-energy-type ammunition). The following intuitive arguments describe how these factors could depend, to some extent, on bore straightness.

The explosion of gun gases in the chamber moves the projectile forward and the barrel rearward (recoil). The transmission of recoil forces along a curved barrel creates longitudinal and transverse components of force, and hence acceleration, as depicted in Figure 1. Since transverse motion of the muzzle will be imparted to the projectile at shot exit, it can affect projectile jump. Indeed, such circumstances could help explain the results of a recent 25-mm M242 accuracy test (Garner et al. 1995). Cross-barrel temperature differences (CBTDs) indicated that during rapid fire, thermal distortion of the gun barrel increased the curvature of the bore centerline to the gunner's left, while at the same time, the round impacts moved (in general) to the gunner's right, Figure 2. It can be reasoned that the correlation between change in prefiring bore curvature and change in projectile impact location resulted from transverse motion of the muzzle that was imparted to the projectile at shot exit.

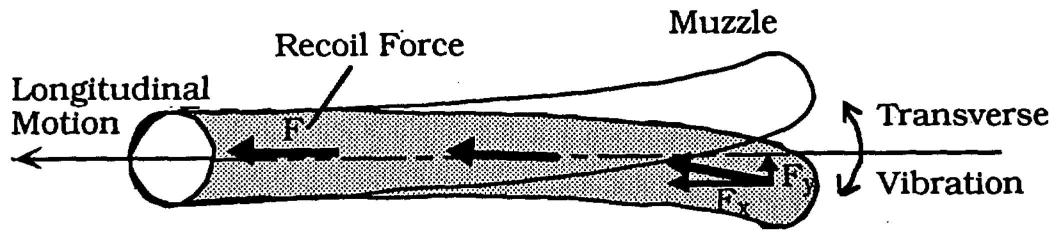

Figure 1. Illustrating the effect of recoil on a curved bore centerline.

In the case of saboted rounds, forcing the projectile to follow the lateral oscillations of a curved bore centerline is thought to produce an asymmetric distribution of compressional energy loads within the elastic sabot petals. This is believed to affect the symmetry of sabot petal separation from the central long rod penetrator, and hence affect the symmetry of aerodynamic side forces (created by shock waves from the discarding sabot petals [Plostins, Bornstein, and Celmins 1991]) on the penetrator before it enters free flight.

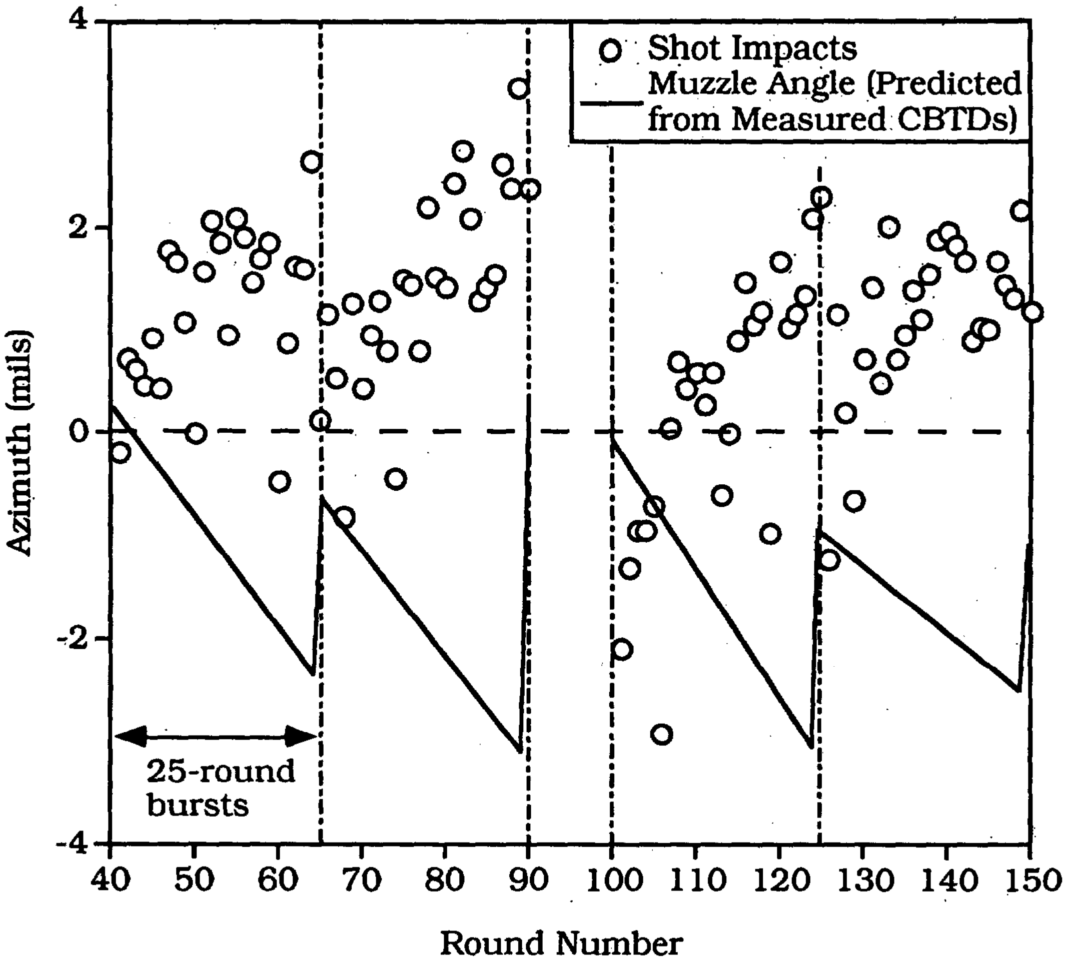

Figure 2. Change in shot impacts and muzzle point angle during four 25-round bursts, with 2 min between bursts (Garner et al. 1995).

To study the relationship between tube straightness (centerline curvature) and projectile jump, we have instrumented a 120-mm M256 gun barrel with temperature-controlled heating pads along its axis, in both the horizontal and vertical planes. The heating pads are used to create a CBTD pattern that changes the bore centerline. Three cases of thermal bend are examined in this report. In each case, a thermal distortion model (Bundy 1993) is used to predict centerline change based on the measured CBTDs. A muzzle borescope and displacement-measuring dial indicators are used to validate the predicted change. At some future date, the barrel will be fired to ascertain the effect of centerline change on projectile jump.

2. INSTRUMENTATION

Twenty 5-in by 14-in (127-mm by 356-mm), 600-W heating pads (made by Ocean State Thermotics, Inc.) were affixed to the external surface of an M256 cannon using thermally conductive silicone rubber (Sylgard 577 by Dow Corning), as illustrated in Figure 3. Each pad was fabricated with a 0.5-in (~13-mm) hole in its center, through which a k-type (Chromel-Alumel) thermocouple monitored the gun barrel temperature. Each thermocouple and heating pad combination was connected to a temperature controller (manufactured by Omega Engineering, Inc.) that turned the heating pad on or off so as to maintain (within a few degrees Celsius) a preset barrel temperature.

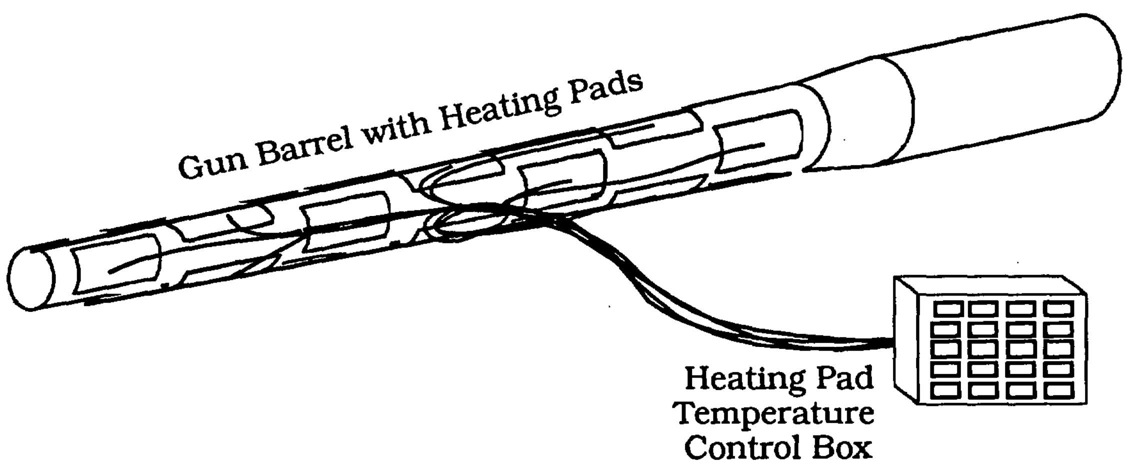

Figure 3. Illustration of temperature-controlled M256 gun barrel.

An unsymmetric heat (pad) input pattern was used to create thermal distortion of the barrel, which was measured in two ways. Dial indicators were used to gauge the off-axis (transverse, or lateral) displacement, while a muzzle borescope was used to determine the change in muzzle pointing angle.

3. TUBE SHAPES

Three different centerline profiles were examined. The first profile attempted to make the bore centerline as straight as possible; the second created a bow-like (half sine wave) curvature in the barrel; and the third shape resembled that of a full sine wave. Bear in mind, these changes are not perceptible to the unaided eye, creating maximum centerline deviations from an end-to-end chord of less than 1 mm (as shown later).

3.1 Straight

The particular barrel chosen for this study (M256 serial number 2971) was manufactured relatively straight. In fact, "2971" is straighter than all 20 of the M256 barrels studied by Wilkerson (1995) in his report on barrel straightness and accuracy. Figure 4 shows a comparison of 2971's centerline with that of a typical barrel in the Wilkerson study (e.g., serial number 4088). The displacement in both planes in Figure 4 is measured relative to a straight-line chord drawn from the muzzle end of the bore, to the chamber end (specifically, from ~230 mm to ~ 4630 mm from the muzzle, which delimits the range of the bore centerline measuring device). A positive value means the bore centerline is displaced above the chord in the vertical plane, and to the (gunner's) right of the chord in the horizontal plane.

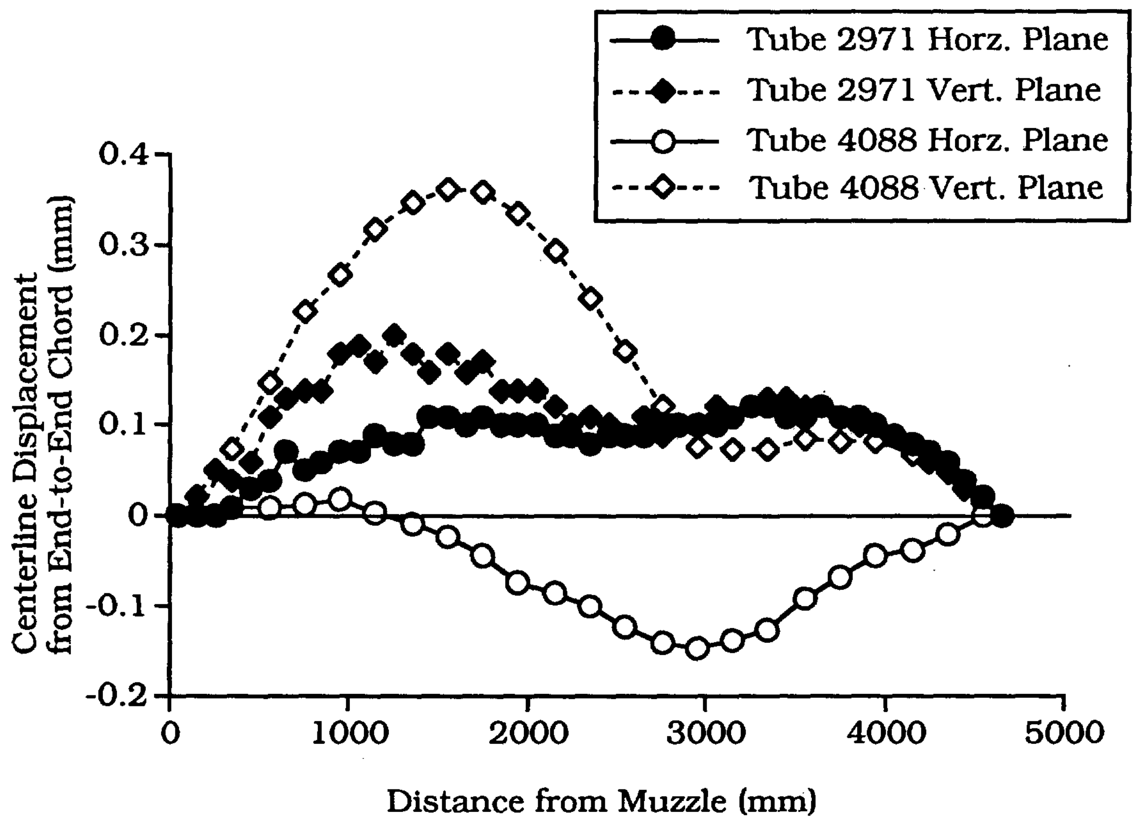

Figure 4. Comparison of centerline straightness for a relatively straight M256, serial number 2971, vs. a more typical M256 barrel, serial number 4088.

In spite of its inherent straightness, the heating pads were used to make 2971 even straighter. This was accomplished with the measured CBTD distribution shown in Figure 5. Note, there is a difference between the preset value for the CBTD and the measured CBTD. This is due, in part, to the fact that each temperature controller will turn on and off within a 1–2° C temperature range about the preset value. But a larger share of the disparity, particularly in the vertical plane, where more heating pads were installed, is due to the fact that heat from each pad migrates axially and circumferentially to the location of nearby heating pads. Furthermore, gravity predisposes the top of the barrel to be hotter than the bottom. As a result, each heating pad must compensate for heat input from nearby heating pads and gravity effects in order to obtain the sought-after CBTD profile.

It should also be pointed out that there is only one measured CBTD for every pair of laterally opposed heating pads. Nevertheless, close inspection of Figure 5 reveals that three CBTDs have been apportioned to the region spanned by each pad. The assignment of three CBTDs from a singular measurement is based on the a priori assumption that the region of the barrel under the central third of the pad is at the measured CBTD, while the outer two thirds are assumed to have half of this value. As is shown later, this prescription for assigning CBTDs leads to reasonably good agreement between theory and experiment, particularly in the horizontal plane. We shall henceforth refer to the assigned CBTDs as simply the measured CBTDs.

Figure 6 displays the predicted effect on straightness of two measured CBTD profiles, one of which is shown in Figure 5. The square-shaped symbols mark the inherent (manufactured) centerline curvature for tube 2971. The diamond-shaped symbols outline the predicted centerline change brought about by measured CBTDs from two different trials; and the circle-shaped symbols are a summation of the manufactured curvature with the CBTD-induced curvature.

Even though there is variation in the level of straightness from one trial to the next in Figure 6 (due to the on-off tolerance level in each temperature-controlling device), there is at least a twofold increase in straightness of 2971 that is brought about by use of the heating pads.

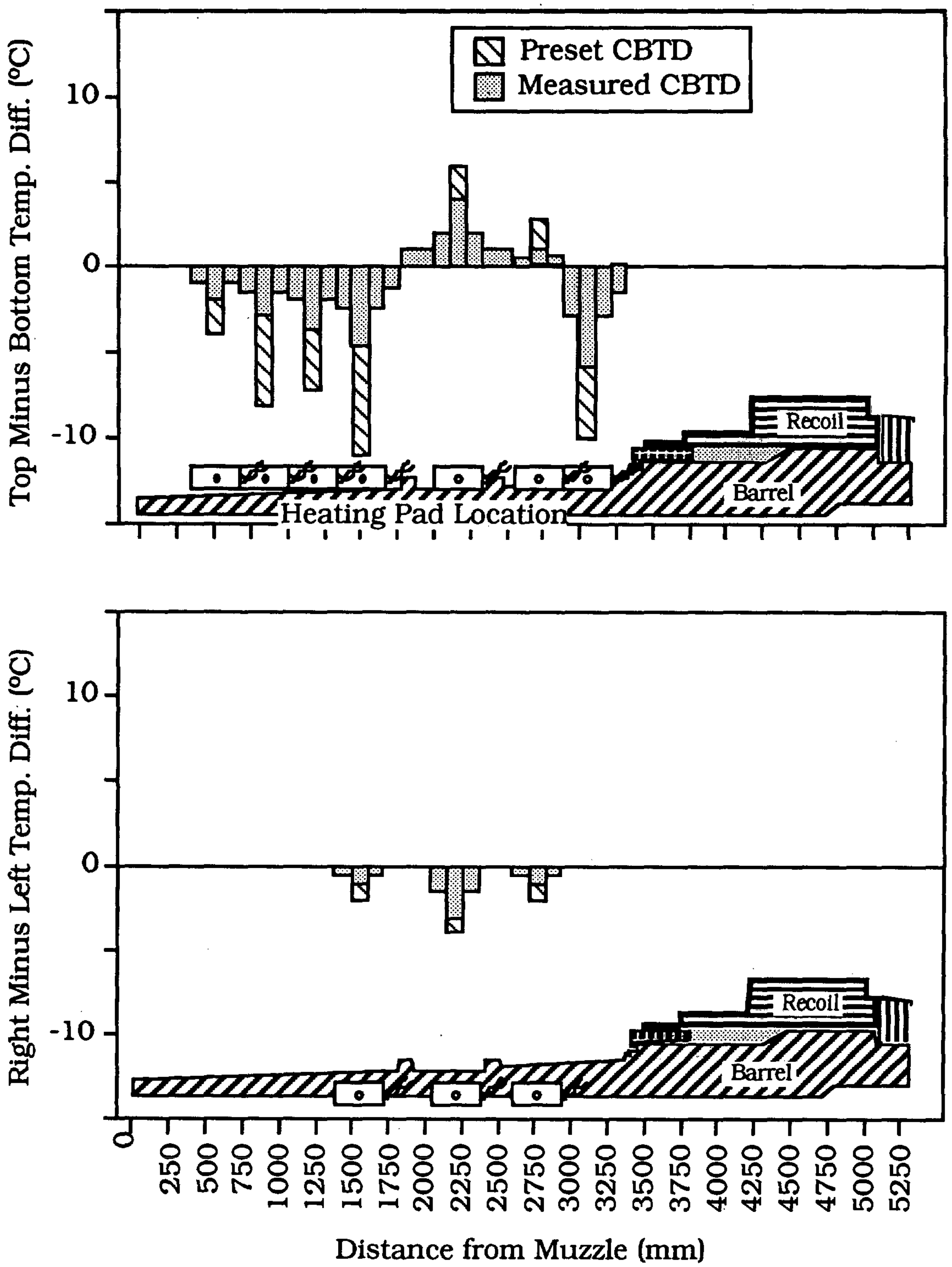

Figure 5. Cross barrel temperature difference (CBTD) needed to further straighten M256 serial number 2971 in the vertical (top plot) and horizontal (bottom plot) planes.

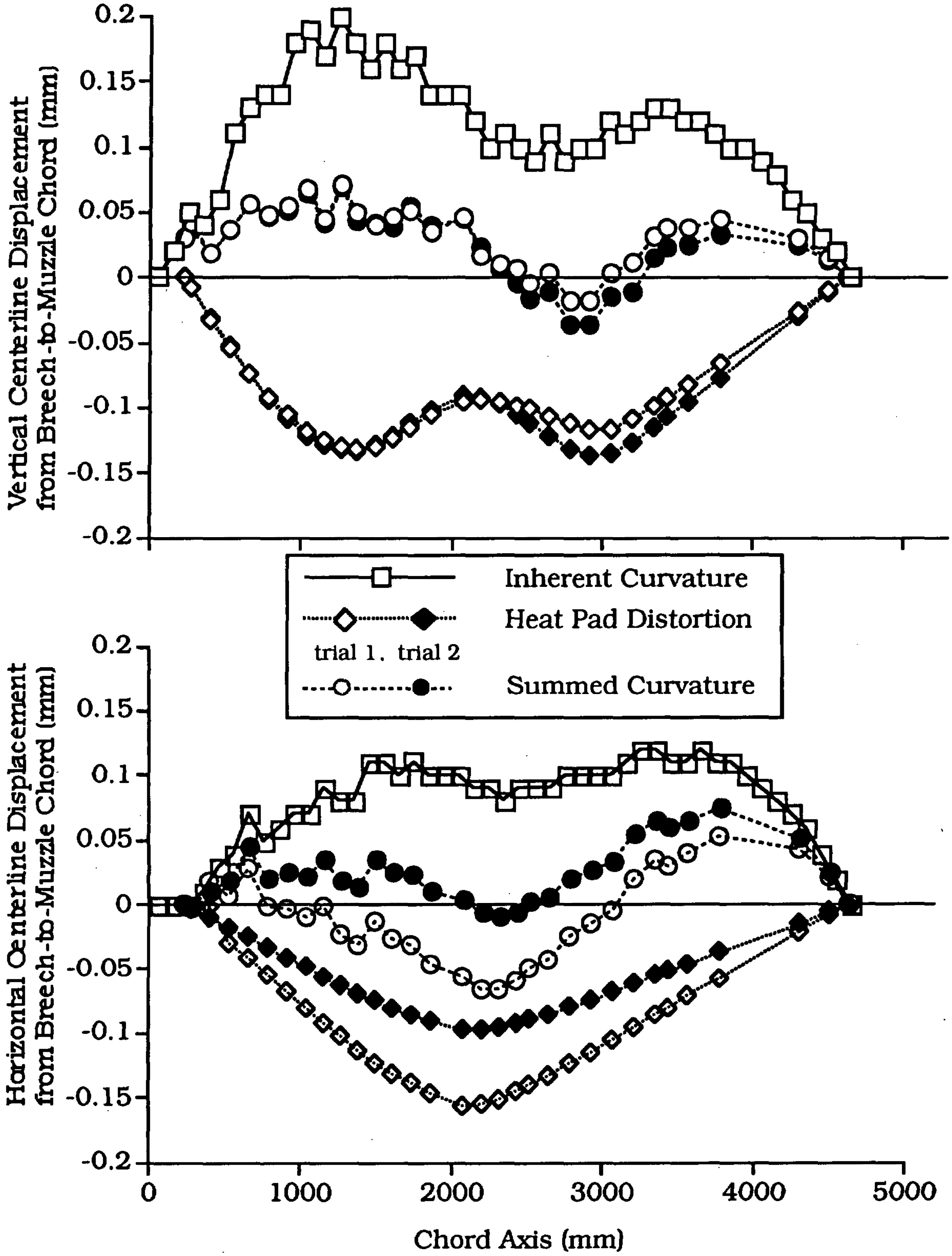

Figure 6. Temperature-controlled straightening of M256 serial number 2971, in the vertical (top) and horizontal (bottom) planes.

We would expect the summed curves in Figure 6 to be close to that which could be measured during these heating pad trials, if it were it not for the fact that critical optical components in the centerline measuring device will not function properly in the turbulent bore atmosphere created by heating the barrel. Since it is not possible to directly measure the bore straightness with the heating pads in operation, the model is validated by comparing predictions with measurements of the muzzle angle and off-axis displacement of the outer barrel wall (using standard machinist's dial indicators). Figure 7 shows such a comparison.

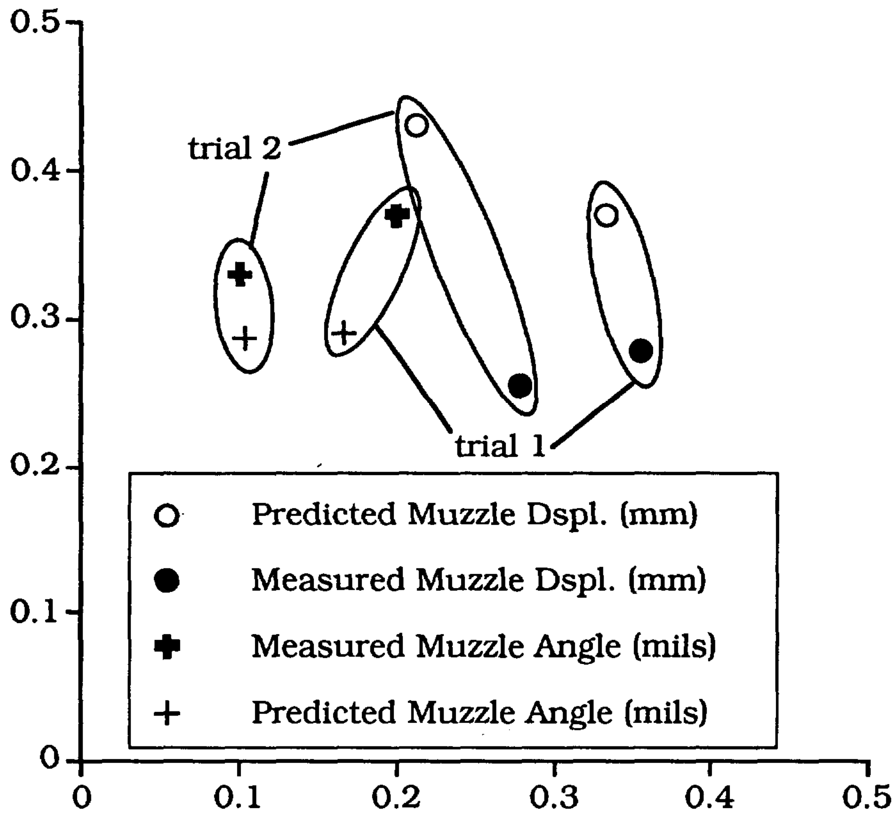

Figure 7. Comparison of CBTD-based prediction vs. measurement of muzzle angle and muzzle displacement induced by heating pad pattern used to further straighten M256 serial number 2971.

As can be seen, the angular difference between theory and experiment is at most 0.1 mil, while the displacement difference can vary by 0.2 mm (0.008 in). In general, the agreement is better in the horizontal plane than in the vertical plane. Additional comparisons will be shown for other tube shapes.

3.2 Half Sine Wave

Many bore centerlines have a simple bow, or half sine wave shape (Wilkerson 1995), perhaps 50%. The heating pattern shown in Figure 8 was used to create such a shape in 2971. It can be seen that CBTDs greater than 20° C can be obtained with the heating pads. (For comparison, a CBTD of 26° C was observed when rain-like precipitation impinged on a hot, post-fired barrel [Bundy 1987]). Figure 9 shows how this type of left-sided heating pattern deflected the barrel to the right, relative to the unheated state. As shown, the measured and predicted displacement differed by less than 0.1 mm at two arbitrarily chosen locations on the barrel.

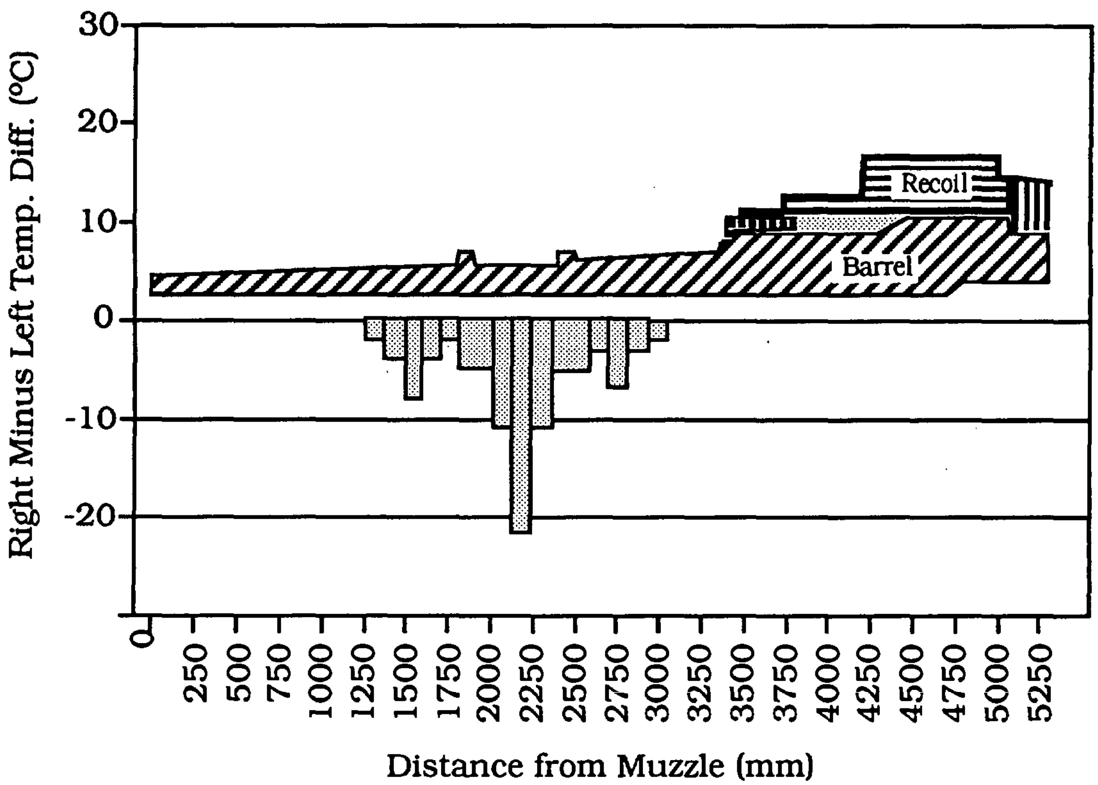

Figure 8. Heat-pad-induced CBTD profile used to create a half sine wave bore centerline curvature.

Figure 9 references a particular time during heating; Figure 10 shows how theory and experiment compare over time during the heating process. In general, the muzzle angle comparison agrees within 0.1 mil, while the muzzle displacement agrees within 0.2 mm, as was the case in Figure 7.

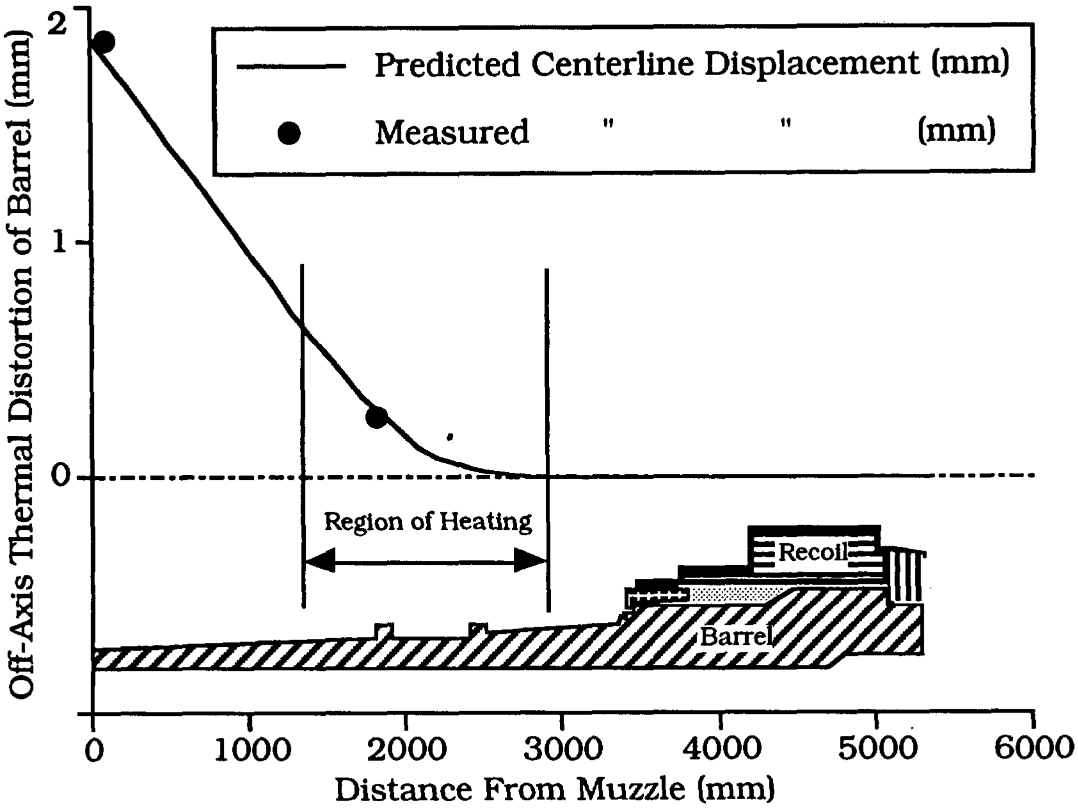

Figure 9. Change in bore straightness due to Figure 8 heating.

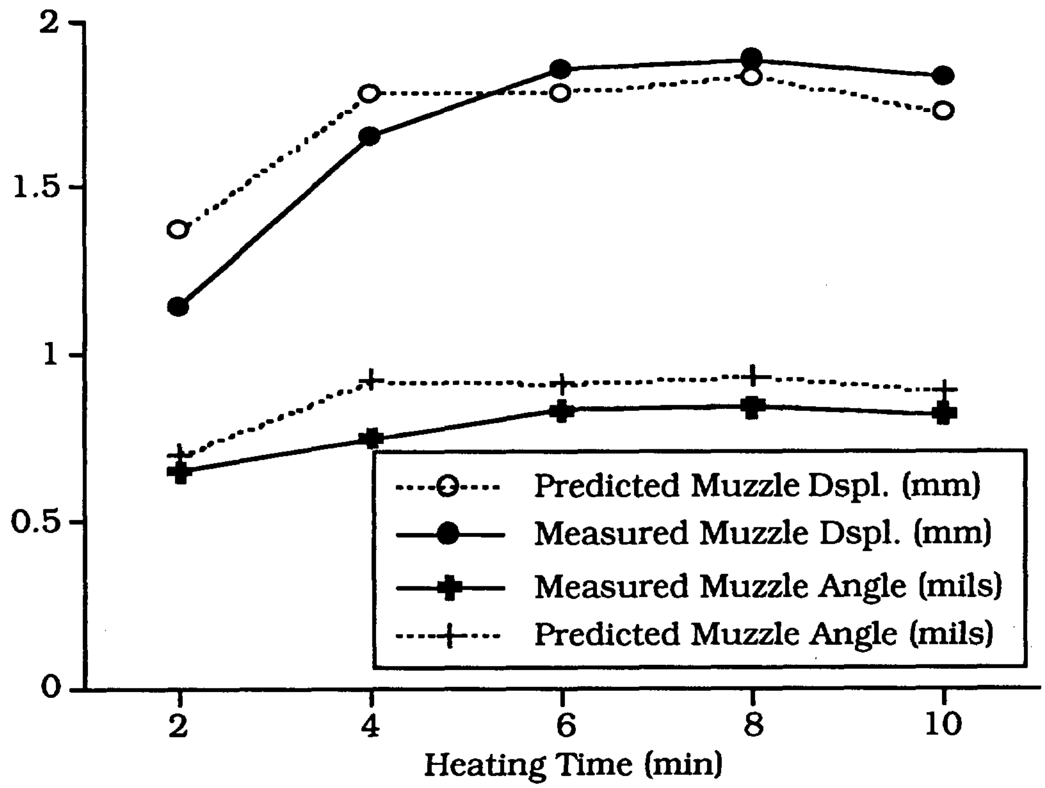

Figure 10. Comparison of prediction vs. measurement over time.

The left-sided heating of Figure 8 creates a centerline change that is several times larger in magnitude than the natural bore curvature, Figure 11.

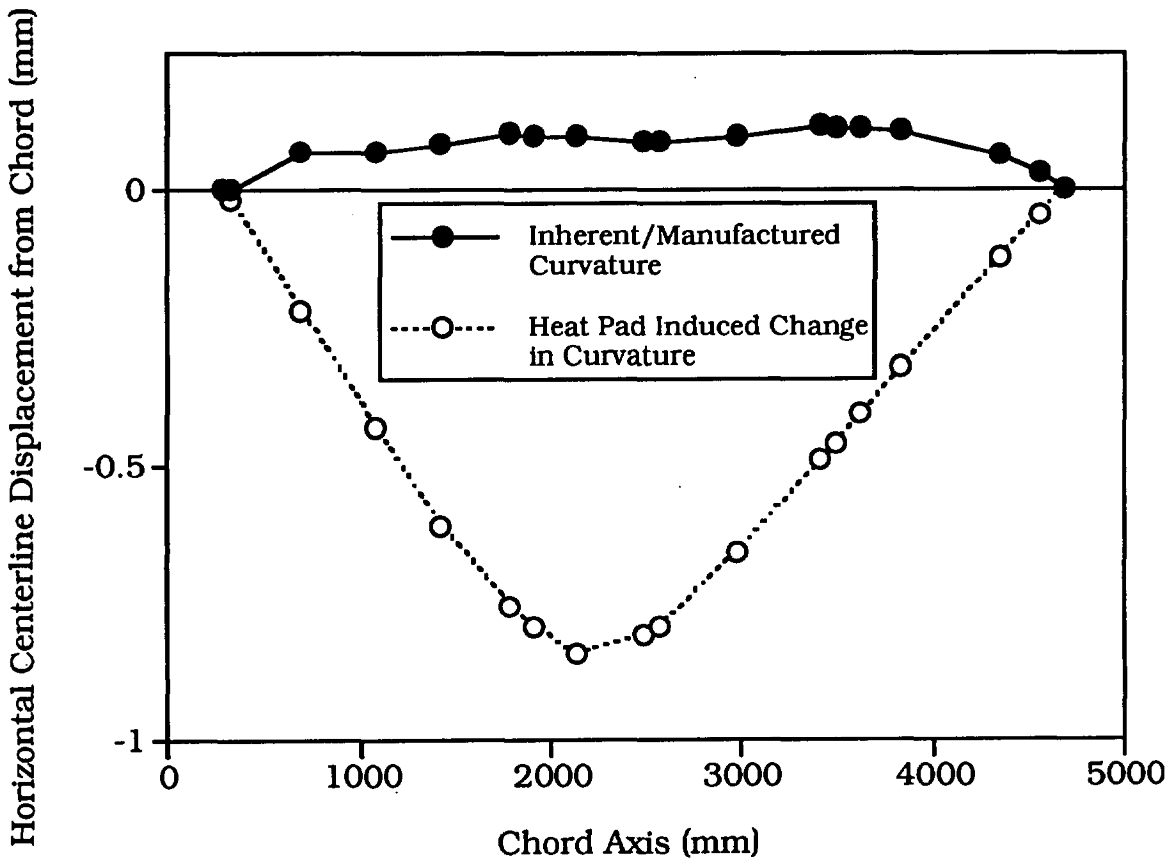

Figure 11. Centerline change due to left-sided heating of Figure 8, compared to the natural horizontal curvature of tube 2971.

3.3 Full Sine Wave

The CBTD pattern shown in Figure 12 was used to create the full sine wave distortion shown in Figure 13. Dial indicators placed at three locations along the barrel show, Figure 14, that the predicted curve underestimates the measured shape change by 10–20%. Moreover (not shown), the predicted muzzle angle was 0.18 mil compared with the measured muzzle angle of 0.32 mil. Even though the differences between theory and experiment are larger in Figure 14 (vertical plane) than they were in Figure 9 (horizontal plane), the differences are not large in comparison to the overall shape change. In perspective, the difference in fall of shot from the predicted vs. the measured shape change in Figure 14 is expected to be far less than that produced by its mirror image, due to reversing the CBTD heating profile.

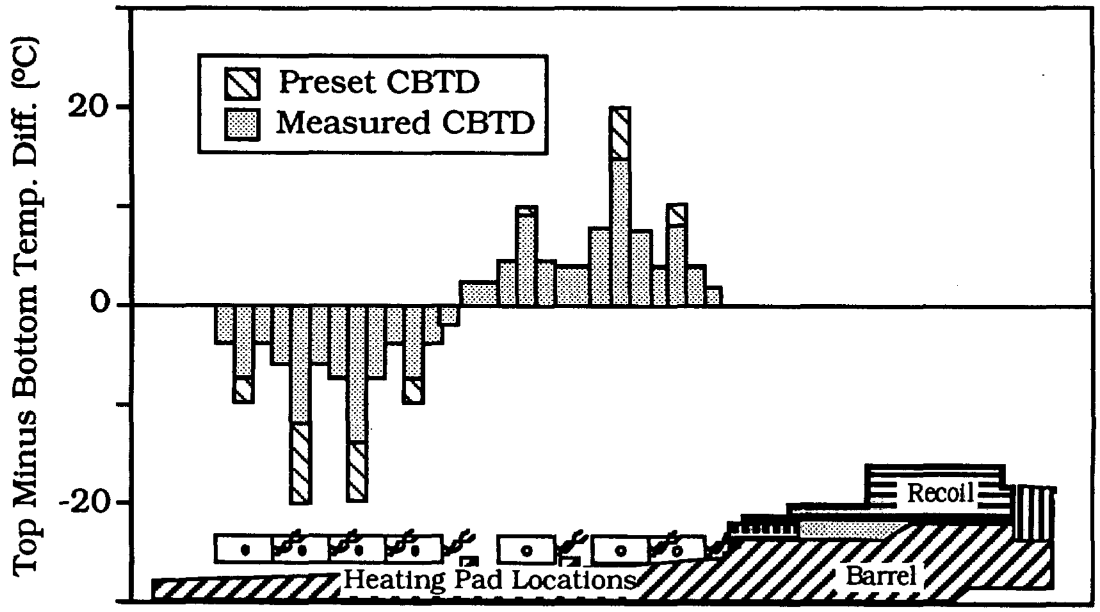

Figure 12. CBTD pattern used to create a sine-wave-like thermal distortion of the barrel.

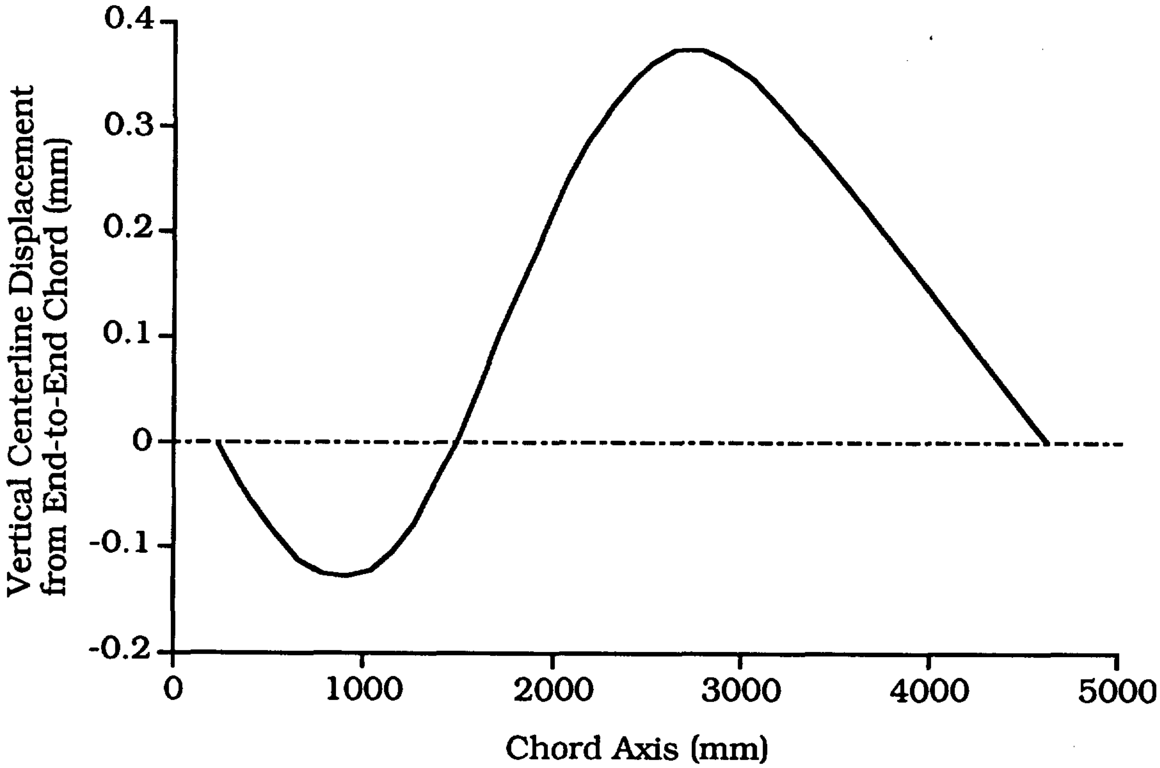

Figure 13. Predicted bore centerline change, relative to the straight-line muzzle-to-chamber chord, due to the CBTD pattern of Figure 12.

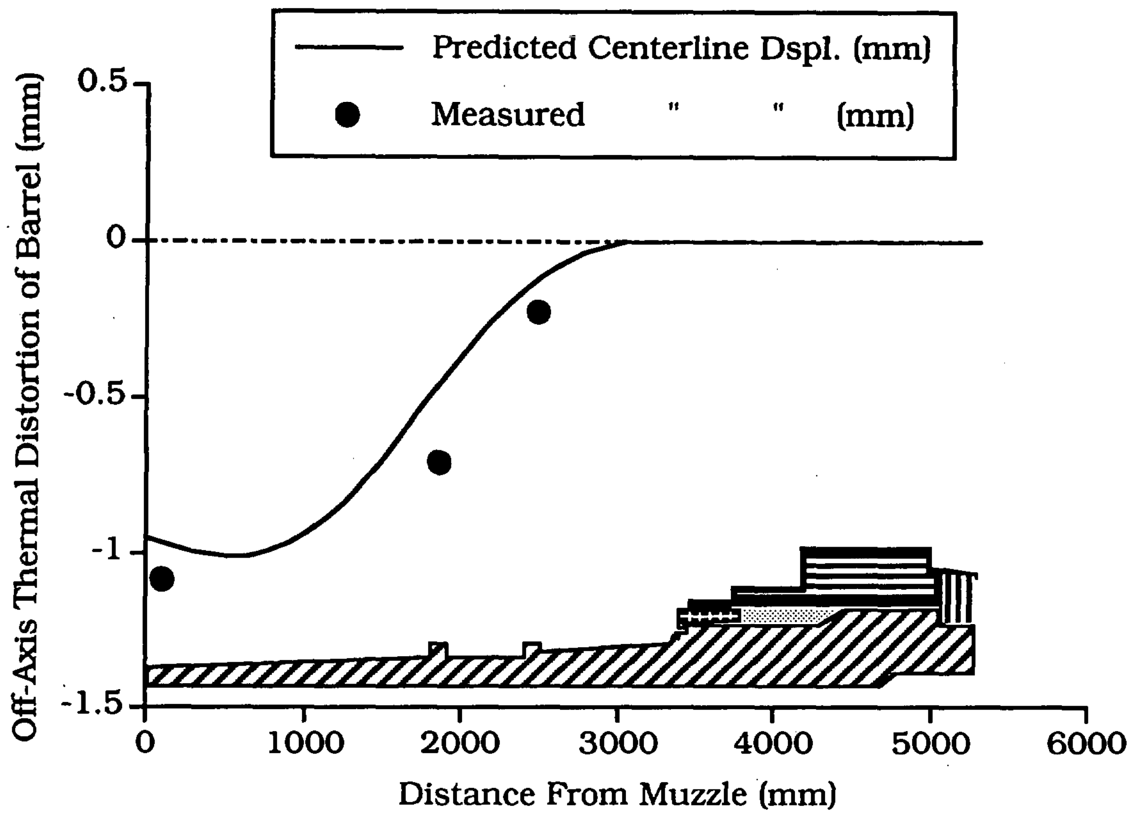

Figure 14. Comparison of CBTD-based prediction vs. measurement of lateral barrel displacement induced by heating profile of Figure 12.

4. CONCLUSIONS

Heating pads were used to thermally distort the barrel, as demonstrated by creating three different tube shapes, viz., a straight tube, a half, and a full sine wave shape.

A thermal distortion model, based on measurements of the cross-barrel temperature differences, CBTDs, was used to predict/estimate the overall centerline shape change. It was not possible to measure the CBTD-induced shape change with a conventional (optically based) centerline measuring instrument, due to hot-air turbulence in the bore. Instead, the thermal distortion model was validated by comparing the predicted vs. measured muzzle angle (using a muzzle borescope), as well as the predicted vs. measured off-axis barrel displacement (using dial indicators).

As a whole, the prediction and measurement agreed fairly well—the muzzle angle values were within 0.1 mil (for comparison, the error in the muzzle scope reading is considered to be 0.05 mils), and the displacement values were within 0.2 mm (0.008 in).

Elaborating, the agreement between theory and experiment appeared to be better in the horizontal plane than in the vertical plane. It could be the case that the postulated distribution of barrel temperature beneath the pad is not as universal as was assumed. That is, the barrel section under the middle third of the heating pad was assigned the pad-centered CBTD measurement; whereas the barrel sections beneath the outer two thirds of the pad were assigned half the measured value. This assumed distribution of barrel temperature across the pad, based on one central-pad measurement, seems to provide better results in the horizontal plane, where the spacing between pads is slightly greater, than in the vertical plane. Nevertheless, the magnitude of the discrepancy is not sufficient to warrant further refinement in the predictive procedure at this time. It is expected that a bow-, or s-shaped, curve to the right vs. left, up, or down, will have a far larger affect on shot impact than the 10-20% discrepancy between the predicted and measured/actual barrel curvature.

Future live-fire tests will examine the influence of centerline shape on projectile impact locations by firing, for example, a bow shape to the right vs. left, and noting the difference, if any, in the fall-of-shot pattern.

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